Flexible and Conformal Thermal Ground Planes

Christopher Oshman[1], Qian Li[1], Wei Wang[1], Ching-Yi Lin[1], Li-Anne Liew[1], Aziz Abdulagatov[1], Ming Kong[1], Susan Song[1], Xianming Dai[2], Ronggui Yang[1], Chen Li[2], Steven M. George[1], Victor M. Bright[1], Suraj P. Rawal[3], Robert J. Monson[3] and Yung-Chen Lee[1]

[1]University of Colorado at Boulder, Boulder, CO 80309, U.S.A.
[2]University of South Carolina, Columbia, SC 29208, U.S.A.
[3]Lockheed Martin Corp., Denver, CO

Abstract: *We report novel flexible thermal ground planes (FTGPs) based on heat pipe technology. FTGP's effective thermal conductivities are much higher than those of copper and graphite heat spreaders'. We report mylar-aluminum, copper-Kapton, and all-polymer FTGP prototypes and advanced technologies which will further enable high-performance FTGPs.*

Keywords: flexible; thermal ground planes; heat pipe; copper, thermal management; atomic layer deposition.

Introduction

Various strategies have been employed for thermal management of electronics and integrated circuits including: forced convection, liquid cooling, solid-state cooling and refrigeration, heat spreaders include high thermal-conductivity materials, as well as vapor chambers and heat pipes. Flexible and conformal thermal ground planes (FTGPs) are enabling components for effective thermal management of future electronic systems. A FTGP follows the same thermal transport principle as that of a heat pipe but possesses superior features because it is two-dimensional and is also flexible and conformal resulting from the polymer-based structural layers.

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Figure 1 shows a FTGP prototype demonstrated and a mechanical scaled-up model. The FTGP is made from polymer-and-metal laminates. The polymeric layer gives it flexibility while the metal layer provides hermetic sealing needed for heat pipe operation.

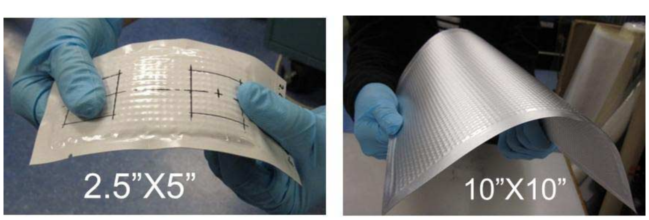

Figure 1. Photographs of FTGPs under development. Left: working prototype. Right: scaled up model.

Figure 2 shows how FTGPs may be used as flexible heat spreaders for electronics cooling in handheld devices. The state of the art is flexible graphite heat spreaders, such as GrafTech International's eGRAF SpreaderShield™. This graphite heat spreader has variable in-plane thermal conductivity up to 1500 W/mK, but its through-thickness thermal conductivity is up to 2 orders of magnitude lower. The FTGP has the potential to outperform graphite due to its higher effective thermal conductivity (2,000 to 5,000 W/mK) as well as its much lower vertical thermal interface resistance from the chip-to-FTGP.

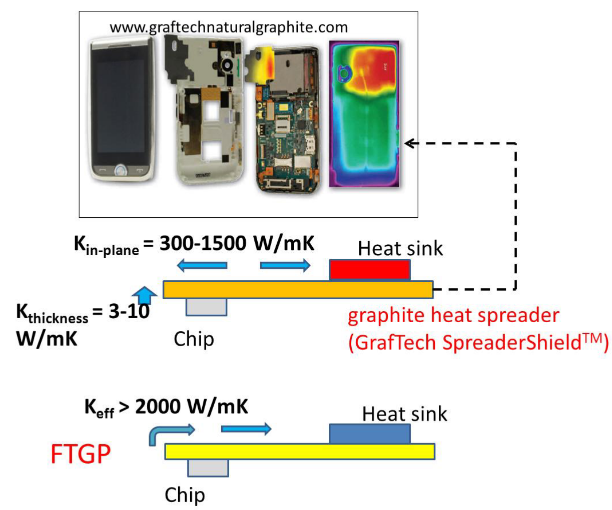

Figure 2. Illustration of a graphite heat spreader application, and FTGP's enhanced capability to replace graphite.

The novelty of our FTGP technology lies in the fact that it is a 2D heat pipe that is thin, flat, flexible (not just bendable), and inexpensive to fabricate. Figure 3 shows our FTGP with 90-degree bending [1]. As shown in the figure, a commercial flat ceramic heater is placed at one end (the "evaporator") to provide an input heat flux. The FTGP's other end (the "condenser") is placed in contact with a heat sink, in this case a liquid cooled coldplate. The figure of merit for the FTGP is its thermal resistance, or *Rth*:

$$R_{th} = \frac{\Delta T}{Q} \qquad (1)$$

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14. ABSTRACT
We report novel flexible thermal ground planes (FTGPs) based on heat pipe technology. FTGPs effective thermal conductivities are much higher than those of copper and graphite heat spreaders. We report mylaraluminum, copper-Kapton, and all-polymer FTGP prototypes and advanced technologies which will further enable high-performance FTGPs.

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where ΔT is the temperature difference between the evaporator and condenser, and Q is the heat extracted from the condenser (which should theoretically equal the input heat from the ceramic heater if there are negligible heat losses from the FTGP surfaces). *Rth* and thermal conductivity are inversely proportional, therefore it is desired that the *Rth* be as low as possible. In Figure 3, the evaporator is placed at the vertical end, thereby forcing the FTGP to work against gravity. The *Rth* is around 1.6 K/W, which is not affected by the bending angle. As a reference, the *Rth* is over 20 K/W without water charged. This FTGP prototype works effectively as a 2-D heat pipe with good flexibility. Details of this study will be published in the near future [1].

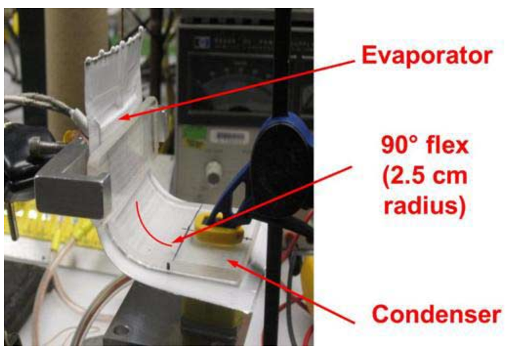

Figure 3. Photograph of FTGP made from mylar-aluminum, being bent at 90°.

We have developed 3 versions of the FTGP, based on different structural materials but with similar design and manufacturing approach using commercially-available materials and manufacturing technologies. The FTGP in Figure 3 was made from mylar-aluminum laminates and was our first test bed for developing this approach to making such 2-D heat pipes. From there, we have developed other versions of the FTGP by using different materials but following the same design, operating principles, and manufacturing processes. Figure 4 shows a FTGP made from copper-clad Kapton and a simple experimental setup. Its *Rth* values measured are around 1.5K/W, which is much lower than 3.5 K/W of an equivalent copper reference. The FTGP and copper reference were each 1.7mm thick. This copper-clad Kapton FTGP is much more thermally conductive than the copper reference. The commercially available graphite heat spreader with a thickness close to 1 mm has thermal conductivity close to 400 W/mK. Its thermal performance is worse than copper because of its low out-of-plane thermal conductivity (see Figure 1). As a result, this copper-clad Kapton FTGP is expected to be more thermally conductive than the graphite heat spreader. It should be noted that FTGP performance can be further improved by using thermal vias as illustrated in the next section.

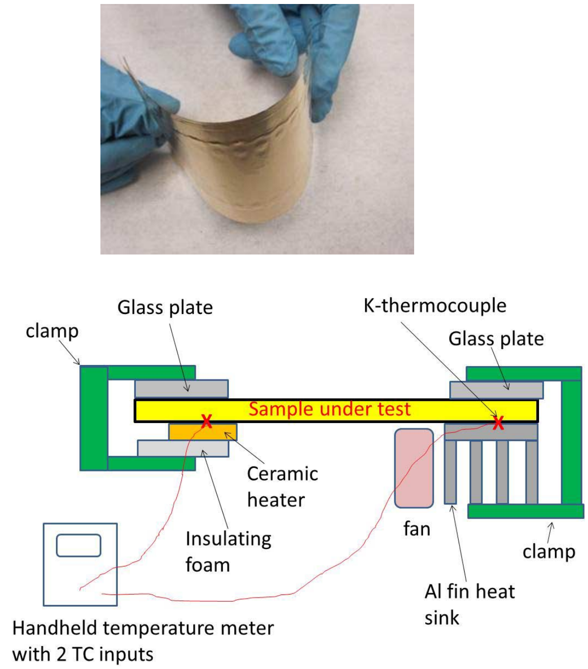

Figure 4. Photograph of copper-clad Kapton FTGP and the simple experimental set up [1].

A third version of our FTGP is made using all-polymer materials, both for the outer casing as well as the internal wicking structures. Figure 5 shows a photograph of the all-polymer FTGP. The *Rth*, measured using the set up in Figure 4, decreased from 14.7 K/W to 5.1 K/W when the heater input power was increased from 5 W to 20W. This decrease in *Rth* with increasing power shows that the all-polymer FTGP is functioning as a 2-D heat pipe and is the first demonstrated all-polymer thermal ground plane. The technological advantages of using only polymers include increased flexibility and conformability in the form factor, much lighter weight than metal TGPs, and inexpensive manufacturing that is easily scalable to large sizes. As this is the first prototype there is much room for performance improvements.

Figure 5. Photograph of all-polymer TGP [1].

Supporting Technologies for Advanced FTGPs

We have developed several technologies that will advance the state of the art in FTGPs.

We have demonstrated printed-circuit-board (PCB) fabrication-based TGPs using copper-clad Kapton and copper-clad liquid crystal polymer (LCP) as structural layers, and with features including microfabricated wick structures, and microfabricated thermal vias. These were reported in our previous publications [2, 3] and shown in Figure 6.

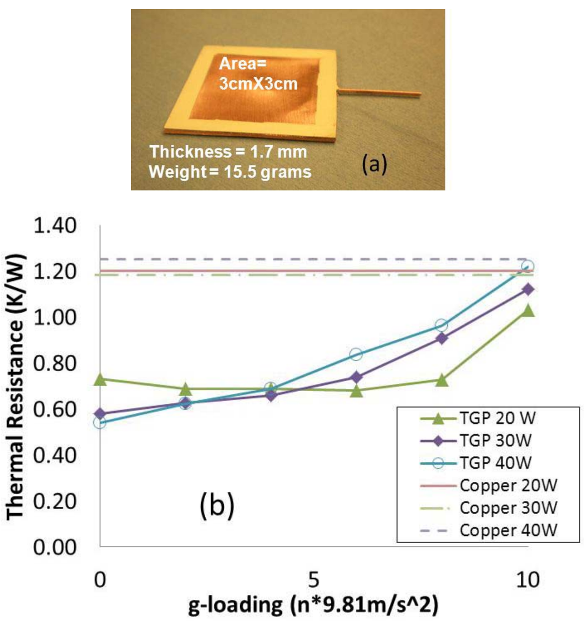

Figure 6. (a) Photograph of PCB-based TGP used in 10-g test (b) thermal resistance of TGP compared with copper, at different g-loading and input power (data is replotted from [2]).

Figure 6 shows a PCB-based TGP that was tested at up to 10-g of adverse gravity. Since TGPs rely on the wicking structures to provide capillary pumping pressure to return the condensate to the evaporator, TGPs in general are susceptible to performance degradation under adverse acceleration. The wicking structures must be able to function against the hydrostatic pressure drop caused by gravitational acceleration. The PCB-based TGP was tested under high-g loading in a centrifuge by Army Research Laboratories (contact: Dr. Brian C. Morgan) and the results shown in Figure 6 show that the TGP maintained much lower *Rth* than for an equivalent copper reference, at up to 10-g, and for various heater input powers ranging from 5 – 40 W.

Hermetic sealing is critical to the long term reliability of TGPs. To support the development of the PCB-based TGP, we developed hermetic sealing technology for LCP based on solder bonding. We then developed non-solder technologies to enable flexibility. Figure 7 shows the results of hermeticity tests on a test vehicle, which consisted of a sheet of copper-clad Kapton bonded to an evacuated and water-containing copper cavity using Fluorinated Ethylene Propylene (FEP) adhesive [4]. The test vehicle was placed in an oven at 100 ^{o}C and the change in weight from water loss was measured over time. Figure 7 shows that the test vehicle exhibited less than 1% yearly weight loss at 100 ^{o}C over a period of 250 days.

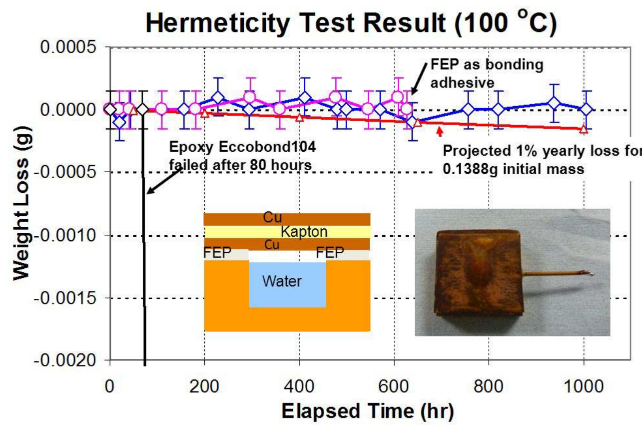

Figure 7. FEP hermetic sealing technology for FTGP [4].

We have also developed hybrid micro/nano structures that exhibit significant enhancement of heat transfer and pool boiling, and which show promise as advanced wick structures [5]. Figure 8 shows 3 microfabricated copper square pillars (43 um x 43 um x 20 um tall and with 57 um pitch), copper nanowires (of lengths 4 um and 30 um) and a hybrid structure consisting of the nanowires on top of the micropillars. Pool boiling experiments showed that the heat transfer coefficient and critical heat flux (CHF) are higher for the hybrid structure than for either the micropillars or nanowires alone, and that the long nanowires were more effective than the short nanowires. We have thus found that hybrid micro/nano structures of the configurations we studied can greatly enhance pool boiling performance to remove ultra-high heat flux and show potential for future application in the TGP.

We have also developed water corrosion-resistant barrier layers based on atomic layer deposited (ALD) films of Al_2O_3 and TiO_2 [6]. Figure 8(a) shows that a copper substrate, which is exposed to water at 90^{o}C for 120 days, exhibits a drastic reduction in the percentage of area corroded when coated with ALD Al_2O_3 followed by ALD TiO_2. This barrier coating is critical to the long term reliability of TGPs by protecting copper meshes and by hermetically sealing all polymer TGPs.

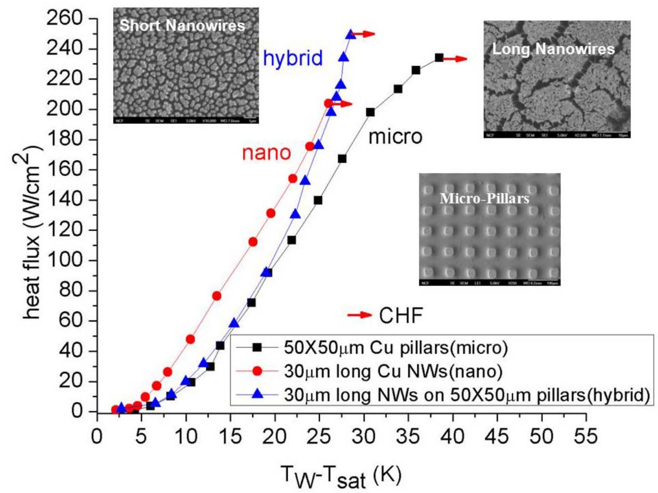

Figure 8. Enhanced criticial heat flux of copper hybrid micropillar/nanowire structures, as next-generation TGP wicking structures [5].

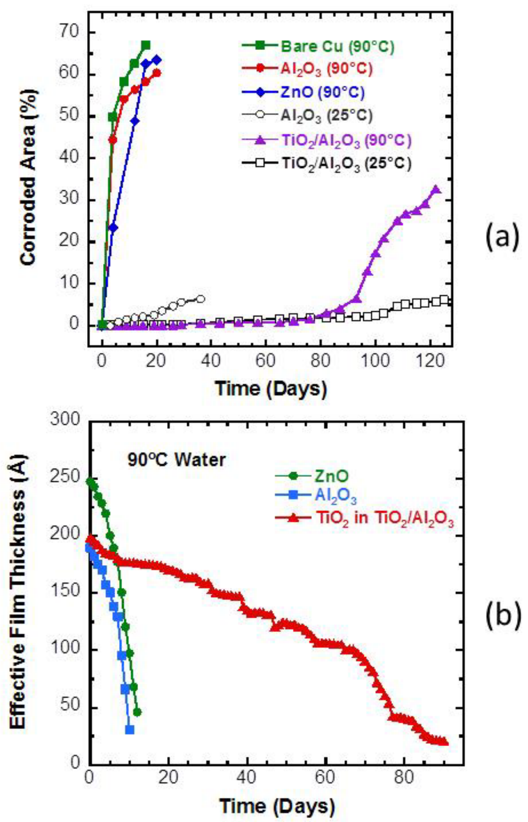

Figure 9. (a) Corroded area of a copper substrate with and without ALD barrier layer (b) ALD thickness over time [6].

Summary and Conclusion

We have developed Flexible Thermal Ground Planes (FTGP) and demonstrate their performance to be superior to that of copper and graphite heat spreaders. We have also demonstrated the first all-polymer FTGP. We then summarized FTGP-enabling technologies: we described our PCB-based TGPs that have been shown to outperform copper at up to 10-g adverse acceleration, and the hermetic sealing technology developed for TGPs. We developed hybrid micro/nano structures which show promise as advanced wick structures by significantly enhancing pool boiling and evaporation heat transfer. Finally, we have demonstrated ALD Al_2O_3 and ALD TiO_2 as effective barrier layers against water corrosion for long term reliability of FTGPs.

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